Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture Team Overview

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LONG-TERM GOALS

UNITES is a unique, interdisciplinary team with expertise spanning the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems. The overall goals of the research are to enhance the understanding of the uncertainty in the ocean environment (including the sea bottom), characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral.

OBJECTIVES

Specific objectives are to:

1) Develop generic methods to efficiently and simply characterize, parameterize, and prioritize sonar system variabilities and uncertainties arising from regional scales (spatial and temporal) and processes.

2) Construct, calibrate and evaluate uncertainty and variability models for sonar systems and their components, addressing forward and backward transfer of uncertainties.

3) Transfer uncertainties from the acoustic environment to the sonar system signal processing in order to effectively characterize and understand sonar performance and predictions.

APPROACH

The UNITES Team characterization and transfer of uncertainty begins with the environment, in particular with spatial and temporal variability in the physical oceanography, and spatial variability in the bottom. These effects impact the acoustics and result in uncertainties in acoustic predictions of propagation, reverberation and ambient noise. These uncertainties impact overall sonar system performance. Our technical approach is based on utilizing environmental uncertainty estimates, i.e. environmental probability density functions (PDF), to provide a probabilistic representation of sonar performance. The PDFs will be determined for appropriate spatial and temporal scales as dictated by

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14. ABSTRACT

UNITES is a unique, interdisciplinary team with expertise spanning the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems. The overall goals of the research are to enhance the understanding of the uncertainty in the ocean environment (including the sea bottom), characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral.

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the systems under consideration. In particular, these PDFs will be determined for: meso- and sub-mesoscale fronts and eddies, tides, internal tides, waves and solitons, interference variability (ambient noise and reverberation) and spatially variable bottoms.

Abbot is the overall team leader and Professor Allan Robinson is the scientific team leader. The following key individuals (ONR Principal Investigators [PI]), their organizations and roles they play on the team, are listed below:

- Allan Robinson and Pierre Lermusiaux, Harvard University (HU) -- ocean modeling and end-to-end data assimilation
- Glen Gawarkiewicz, Woods Hole Oceanographic Institution (WHOI) - physical oceanography measurements and modeling
- Jim Lynch and Tim Duda, WHOI - acoustic fluctuations; Shelfbreak PRIMER and ASIAEX
- Ching Sang Chiu, Naval Post Graduate School - TL estimates and statistics
- Peter Cable , BBN Technologies - bottom reverberation and noise statistics, signal statistics, and processing-induced variability
- Jim Fulford, Naval Research Laboratory - bottom inversion and uncertainty
- Lou Bartec, University of North Carolina - East China Sea bottom uncertainty
- Bob Miller, Oregon State University - stochastic modeling of uncertainty
- Phil Abbot, OASIS Inc. - sonar performance incorporating environmental variability

WORK COMPLETED

Seven of the PIs attended the ONR Uncertainty DRI Review and Planning Meeting held at Scripps Institution of Oceanography in June 2002, and presented tasks completed and technical accomplishments for FY02. Some of the primary tasks and technical accomplishments (including the participating organizations) of the UNITES Team are listed below. (Note, these will be discussed in detail in the FY02 Annual Reports to be submitted by the individual PIs)

* The conceptual basis for the Shelfbreak PRIMER end-to-end system has been specifically defined, including its components, linkages and feedbacks of uncertainty from the environment to the sonar (HU, OASIS).

* Transfer of ocean physical forecast uncertainty to acoustic prediction uncertainty in a shelfbreak environment has been conducted, including histogram estimates of the sound speed and Transmission Loss (TL) uncertainties (HU, NPS). Coupled physical-acoustical data assimilation (DA) was carried out for simulated examples. These advances entailed extending ESSE (Error Subspace Statistical Estimation) to coupled physical-acoustical fields.

* Uncertainties computed via ESSE for the single-frequency forecast TL was processed using a variable-width running-range average to produce an estimate of the uncertainties in the broadband TL term of the sonar equation (HU, OASIS).

* Sonar performance predictions incorporating environmental variability were completed for a passive sonar operating in the East China Sea (ECS) and Sea of Japan (SOJ) (OASIS).

* TL uncertainties in the ECS, including bottom limitations were developed (OASIS, WHOI).

* PRIMER TL and noise fluctuations are being characterized (OASIS, NPS, and WHOI)

* PRIMER modal structures and uncertainty hot spots are being characterized (WHOI).

* Uncertainty predictability and simple rules-of-thumb are being developed based on the PRIMER and ASISEX data sets and simulations (WHOI, OASIS, NPS and HU).

* Bottom reverberation and noise statistics in the Straits of Korea have been characterized (BBN).

* Bottom environmental uncertainty in the ECS has been evaluated using the Minimum Data Density Analysis method (UNC).

* Stochastic modeling of uncertainty, incorporating the Stratonovich calculus has begun (HU, OSU)

We have had meetings with other Uncertainty Teams (Seabed Variability and MIT) and have had fleet transition discussions with COMSUBDEVRON-12, COMSUBPAC and the Sensor Optimization Working Group.

RESULTS

End-to-End System

A conceptual basis of the end-to-end system approach, including its components, was derived and exemplified using shelfbreak-PRIMER data and models. Specifically, a generic approach to: (i) characterize variabilities and uncertainties arising from regional scales and processes, (ii) construct uncertainty models for a generic sonar system, and (iii) transfer uncertainties from the acoustic environment to the sonar and its signal processing, was obtained. Fig. 1 illustrates the forward transfer of information, including uncertainties, in terms of observed, processed and model data (dots on arrows) and products and applications (diamond). The system concept encompasses the interactions and transfers of information with feedback from: i) observing systems, (physical-acoustical-bottom-noise-meteorological-sonar data), ii) coupled dynamical models, (physical-acoustical-bottom-noise-sonar state variables and parameters), and, iii) sonar equation models, (parameters in sonar equations).

Transfer of Environmental Uncertainties to the Sonar and Coupled Physical-Acoustical DA

ESSE was successful in carrying out the estimation of ocean physical and acoustical fields as a single coupled data assimilation problem. Environmental fields and their dominant uncertainties have been predicted and transferred to acoustical fields and uncertainties by an acoustic propagation model. The resulting coupled-dominant uncertainties define the error subspace. The physical and acoustical data are then assimilated such that the total error variance in the error subspace is minimized. This simulation experiment showed that the model can produce simultaneous ocean and acoustic field predictions with reduced errors.

The results of the processing of ESSE uncertainties using a variable-width running-range average to estimate the uncertainties in the broadband TL term of a sonar equation are shown on Fig. 2. The computed environmental PDFs are found to be depth and range dependent. Near the depth of the main wave-guide (55 m), the error standard deviation is relatively constant with range and relatively large, around 3 to 4 (dB). Closer to the surface (30 m) and closer to the bottom (85 m), standard deviations tend to decrease with range (down to 2 dB), leading to a higher PDF peak. The shape of the PDFs (skewness, kurtosis, double peaks, etc.) are also found to be dependent on position with respect to the shelfbreak front.

Environmental Data Analysis

The Shelfbreak PRIMER data set has been used to examine spatial-temporal correlation scales in a shelf edge environment. Modal structures have been examined and show interesting cross-shelf structure. While the dominant mode is similar to that expected by linear stability theory, the second and third modes are different. This suggests that finite amplitude meandering of the front leads to both significant vertical displacement of the seasonal thermocline as well as large cross-shelf excursions of the foot of the front. In addition, an improved climatology of the front has been completed and has been used in a number of propagation calculations by other UNITES team members. The probability density functions of thermal fields in the vicinity of the front have been examined and show complex spatial patterns due to their relative proximity to the mean frontal position.

PRIMER TL Fluctuations

In acoustic field uncertainty characterization and transfer, NPS, WHOI and OASIS, Inc., have focused on the tidal and shorter-scale uncertainties. Using Shelfbreak PRIMER acoustic and oceanographic data, the acoustic uncertainty statistics and their linkages to oceanographic variability were investigated. In particular, daily probability density functions of both transmission loss and noise level were estimated to allow for a quantification of the homogeneity of the inter-daily fluctuations as well as the nonstationarity of the intra-daily statistics.

In the acoustic field uncertainty reduction and forecast, NPS focused on the small mesoscale and longer-scale uncertainties. Also, NPS and WHOI, employing the SeaSoar survey and acoustic transmission data from Shelfbreak PRIMER, demonstrated that daily TL estimates could be upgraded with improved daily ocean estimates.

One of the major acoustics tasks undertaken this year was studying the amplitude variability of low frequency sound propagating through non-linear coastal internal waves, using the New England shelfbreak front PRIMER data as ground truth for both theoretical and modeling efforts. In this work there were two main thrusts. Work by Duda (WHOI) emphasized the mean gain or loss in propagation levels that one would encounter, especially as a function of the source placement relative to the vertical temperature layering in the ocean. This work gives a semi-quantitative guide to what propagation loss biases one might expect for representative sound speed profiles in the littoral, and is immediately useful for our “rules of thumb” approach. Work by Lynch, Colosi, and Fredricks (WHOI) has dealt with the fluctuating, as opposed to the average, part of the pressure field, and has concentrated on four topics. They are: 1) the amplitude and intensity probability distribution functions, 2) the scattering function strength (scintillation index) as a function of range, 3) the physical causes of the amplitude variability seen, and 4) the physical oceanographic “frequency bands” that the variability seems to naturally break into. This work also will be fit into the “rules of thumb” approach.

Sonar Systems Uncertainties

An example using environmental probability density functions for performance predictions is shown in Figure 3. Here, we show predictive probability of detection (PPD) curves for a simulated passive sonar operating in the ECS and SOJ environments. For each environment, two PDFs are used in the prediction, one consisting of the 1-way TL environmental PDF, the other being a System-Based PDF. The latter includes uncertainty in the ambient noise and the source level in addition to the TL and is formed by convolving the 1-way TL environmental PDF with the ambient noise and source level PDFs. The figure illustrates that all classes of variability affect the PPD. Their origins could be environmental (TL, ambient noise or reverberation, if active) or, non-environmental (source level/target strength, self noise, recognition-differential, and the like). The variability controls the slope of the PPD versus range, the larger its total σ, the larger the slope. The PPD provides the system operator with a probabilistic representation of the system performance as a function of range and the slopes provide the basis for trading the gradual range-dependence of detection probability with mission desiderata.

Further, the curves show significant differences of sonar system operation for the two locations, with simulated detection ranges much greater in the ECS. The PPD method is useful for incorporating environmental uncertainty into predictions of sonar system performance.

Reverberation Statistics

Figure 4 shows PDFs for scattering strength determinations obtained from low frequency impulsive source reverberation data from Korea Strait. These statistics establish the amount of echo fluctuation associated with reverberation for a low frequency active sonar operating in this area. As anticipated for a Gaussian process, the instantaneous diffuse reverberation exhibits a constant standard deviation that is independent of the derived scattering strength mean. For the Korea Strait data the standard deviation associated with the instantaneous diffuse reverberation is about 3.8 dB.

IMPACT/APPLICATIONS

The end-to end framework has the ability to assess the aggregate system uncertainty, including individual uncertainty components, in the sonar performance prediction, which can be an invaluable tool in the development of tactical guidance. Coupled four-dimensional data assimilation for physical-acoustical fields has the potential to provide significant advances in physical and acoustical ocean sciences and fleet applications. Another application is to assist the sonar "prediction community" by providing a probabilistic representation of sonar system performance. The present approach provides a systematic method of incorporating environmental uncertainties and transferring their effects in the end-to-end problem through the sonar systems under consideration. The operator can thus use this information to operate the system more effectively and make more informed decisions on search, risk, expenditure of assets (weapons) and assumptions of covertness.

TRANSITIONS

Rules-of-thumb, lessons learned, technical implications for effective environmental sampling strategies for the fleet and other tactical insights will be presented to appropriate fleet personnel. We expect to

transition specific uncertainty ideas (rules-of-thumb, sampling strategies) through the ONR Littoral ASW FNC program (Common Tactical Picture and Advanced Estimation of Sensor Performance) and the Advanced Processor Build (APB) program. We anticipate briefing other appropriate fleet personnel this fall and winter.

Also, the Multi-Static Active ASW System is currently being transitioned to the Navy through the Advanced Systems Technology Office (ASTO). Recognition of the environmental uncertainty on acoustic propagation is important for the development of fleet rules-of-thumb and tactical documents. Present uncertainty analyses are being used by ASTO in the development of a tactical memo for system operation in the ECS environment, including rules-of-thumb for effective source and receiver placements.

RELATED PROJECTS

1 - The Multi-Static Active ASW System is currently being transitioned to the Navy through ASTO and the PPD curves derived from the UNITES Team are being utilized by ASTO in this program.

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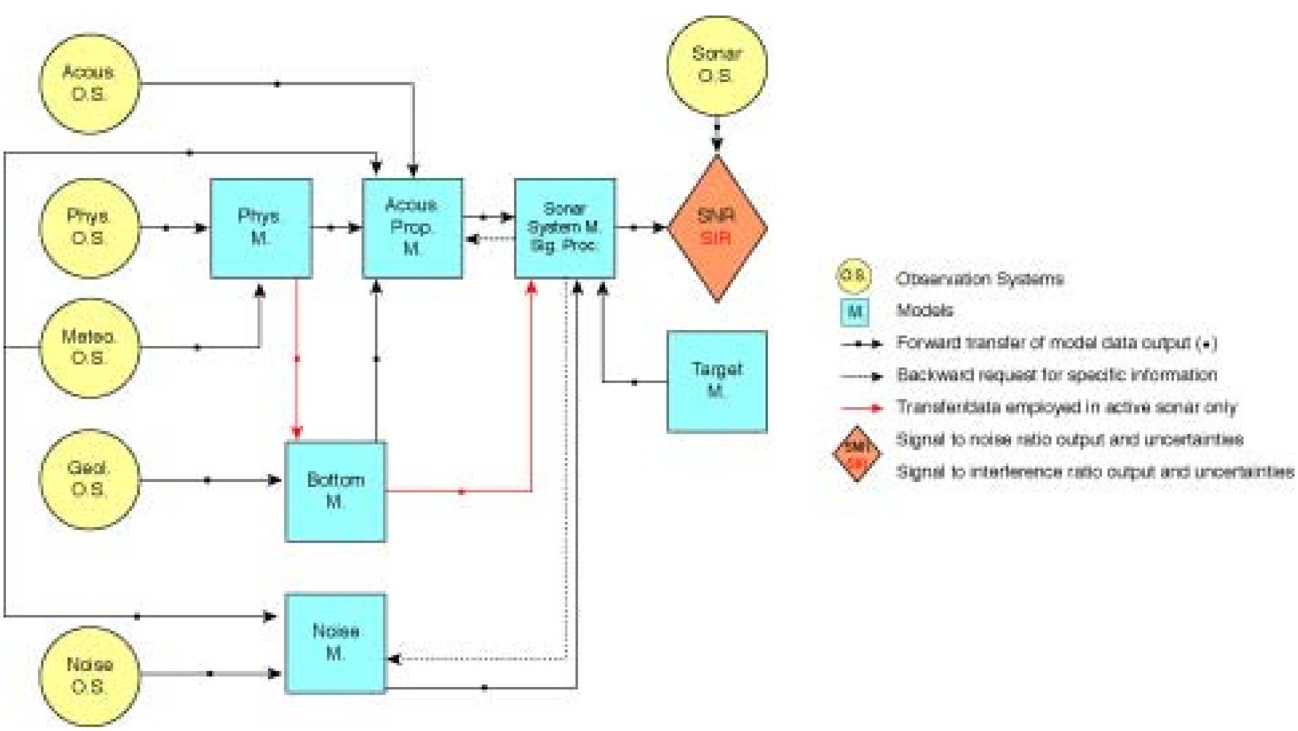

Figure 1. Schematic diagram of the end-to-end system (model point of view).

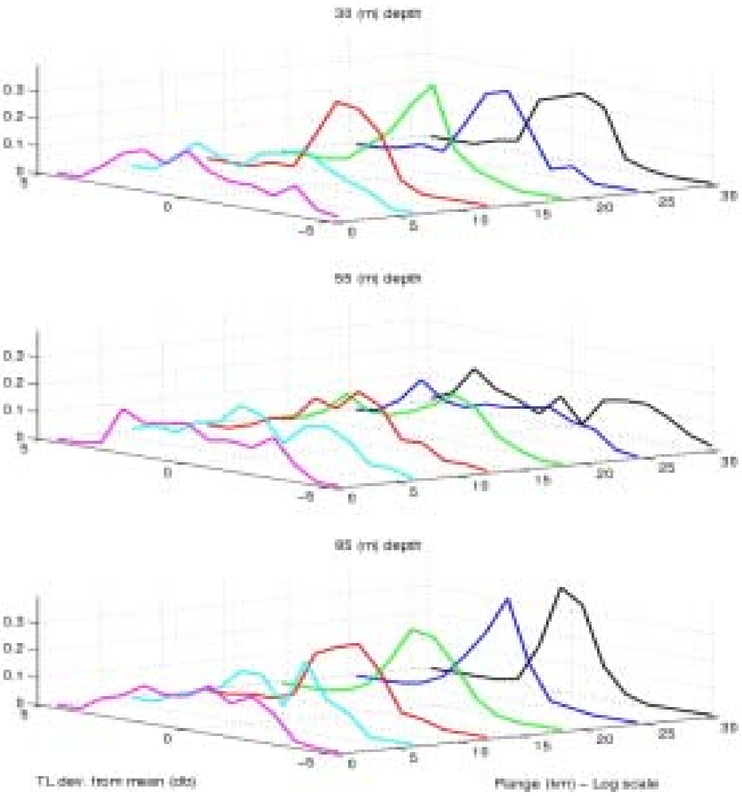

Figure 2. Uncertainty in a broadband TL estimate along a PRIMER path, as computed and transferred by ESSE, from environment, through the acoustic and processing, to sonar equation.

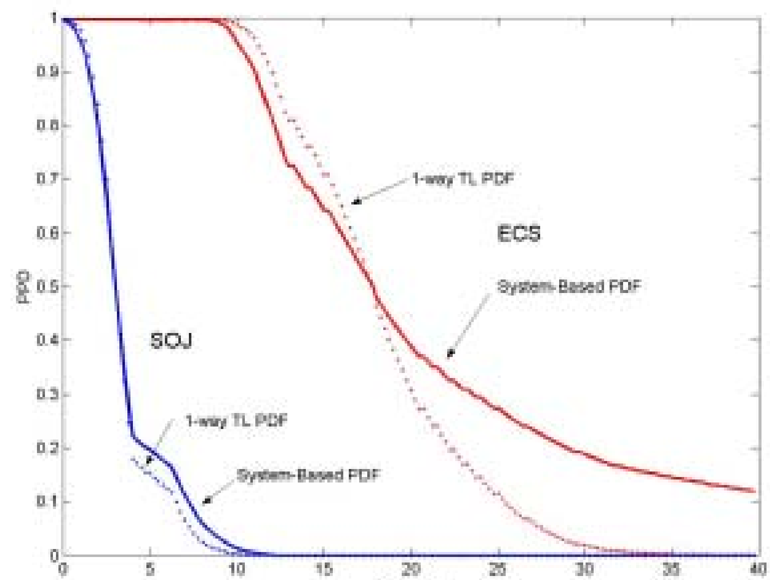

Figure 3: PPD for simulated passive sonar system operating in the ECS and SOJ, during downward refracting sound speed conditions. The dashed lines are based on a single 1-way TL PDF. The full lines include ambient noise and source level uncertainties, as well as 1-way TL.

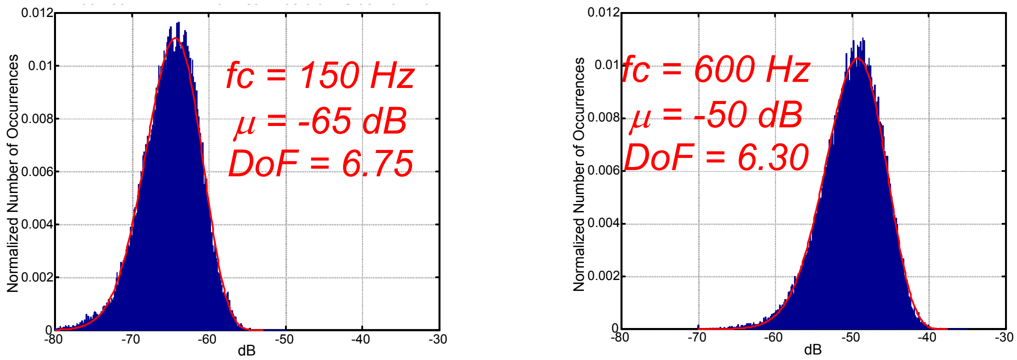

Figure 4. Instantaneous (i.e., time-bandwidth product of one) bottom scattering strength estimates from Korea Strait for octave bands centered at 150 and 600 Hz. The standard deviation of each estimate is about 3.8 dB.